COKE DRUM DESIGN – LONGER LIFE THROUGH INNOVATION

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ABSTRACT

Coke drums tend to suffer from a "bulging" phenomenon due to the cyclic nature of their service. This phenomenon occurs in the lower portion or the “quench zone” of the vessel. The bulges typically are located near the circumferential weld seams joining the cylindrical shell courses. As the number of thermal cycles increase, the bulges grow larger and cause cracking in the vessel shell. The cracking also increases in length, depth and number of cracks as cycle frequency increases. At some point in operation, the cracking must be repaired, the shell sections replaced or the entire vessel replaced for continued safe operation.

Industry studies of operating coking units, which included thermal and mechanical stress analysis, have determined that the circumferential weld seams act as a stiffener during the water quench cycle, causing the shell to distort a short distance above and/or below the weld seam. Several methods to minimize this phenomenon from occurring have been proposed by those in the coking industry, including vessel manufacturers, with only incremental success. This paper describes the bulging phenomena, normally accepted solutions, and a revolutionary method developed by Chicago Bridge & Iron Company to eliminate a primary contributing factor causing the bulging/cracking phenomena.

INTRODUCTION

Industrial petroleum coke is a solid coal-like substance primarily used as a fuel or for the production of anodes, electrodes, graphite or similar carbon based products. Petroleum coke is produced by the “delayed-coking” process. A batch process involving the superheating of heavy residual feed stocks and introducing them into an insulated vertically oriented cylindrical pressure vessel, commonly known as a “coke drum”. Vapors are then drawn off and further refined into various petroleum byproducts, leaving behind a high-density hydrocarbon residue referred to as petroleum coke. The residue is then water quenched to allow the removal of the coke product after the vessel has been depressurized and the coke cooled to the point it will not self ignite when exposed to air.

As part of the delayed coking process, coke drums undergo severe thermal and pressure cycling as the vessel is filled with hot product and subsequently water quenched after coke formation, see Fig.1.

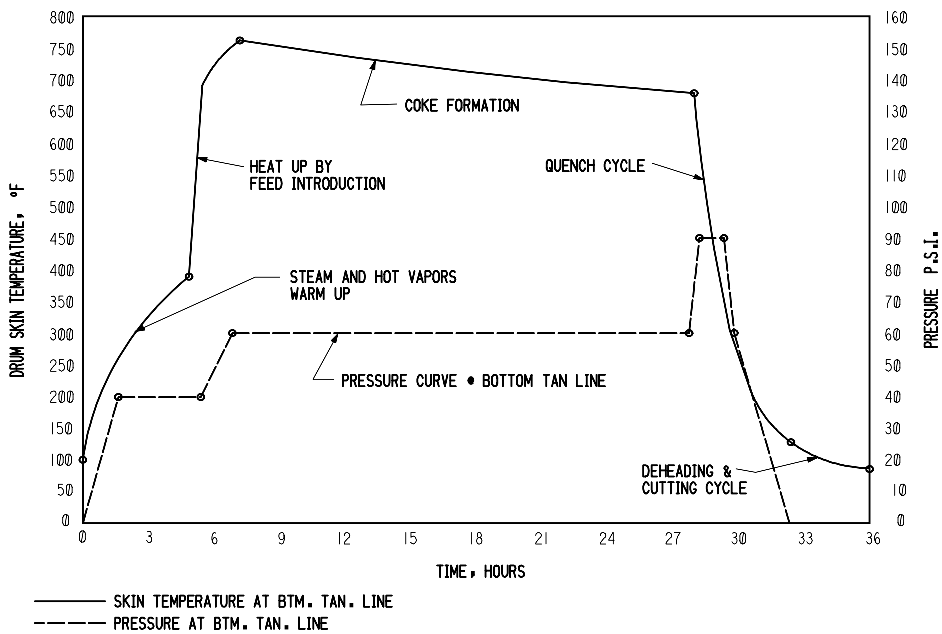

FIG 1 -- A TYPICAL COKE DRUM THERMAL & PRESSURE CYCLE (REF. 5)

The severe heating and quenching rates of the process causes the useful life of coke drums to be shortened vs. that of other pressure vessels operating in non-cyclic conditions. In addition, coke drums typically experience significant down time during their useful life to make needed repairs or partial shell replacements due to the damage caused by the service conditions.

To extend useful life and reduce down time, coke drums which were constructed from mild steel in the early days have in recent years been constructed from low alloys such as Carbon-1/2 Moly, 1 Chrome-1/2 Moly and most recently 2 ¼ Cr – 1 Mo or even higher alloys. With the exception of the 2 ¼ Cr and higher alloyed drums, coke drums manufactured with these materials have all failed in time. Coke drums manufactured from the 2 ¼ Cr and higher alloy materials have been in service only a few years and have not yet endured enough cycles to demonstrate improved reliability. Most modern coke drums are clad with type 410S or 405 stainless steel for resistance to corrosion caused by the high sulfur content in the feedstock. Welding filler metals are normally chosen based on the type of backing and clad (if any) as specified by the final owner/user.

It is the thermal cycling that tends to be the root cause of the bulging and eventual cracking experienced in most applications. Depending on the operating parameters, type of coke produced, feedstock and other variables, the cycle time of a given unit can be from as little as 14 hours (or less) to more than 36 hours. Industry recognizes that the shorter and more severe the cycle the sooner and more pronounced the bulging/cracking will appear. The following photograph, Fig.2, is from a coke drum shell replacement project and illustrates the severity of the distortion.

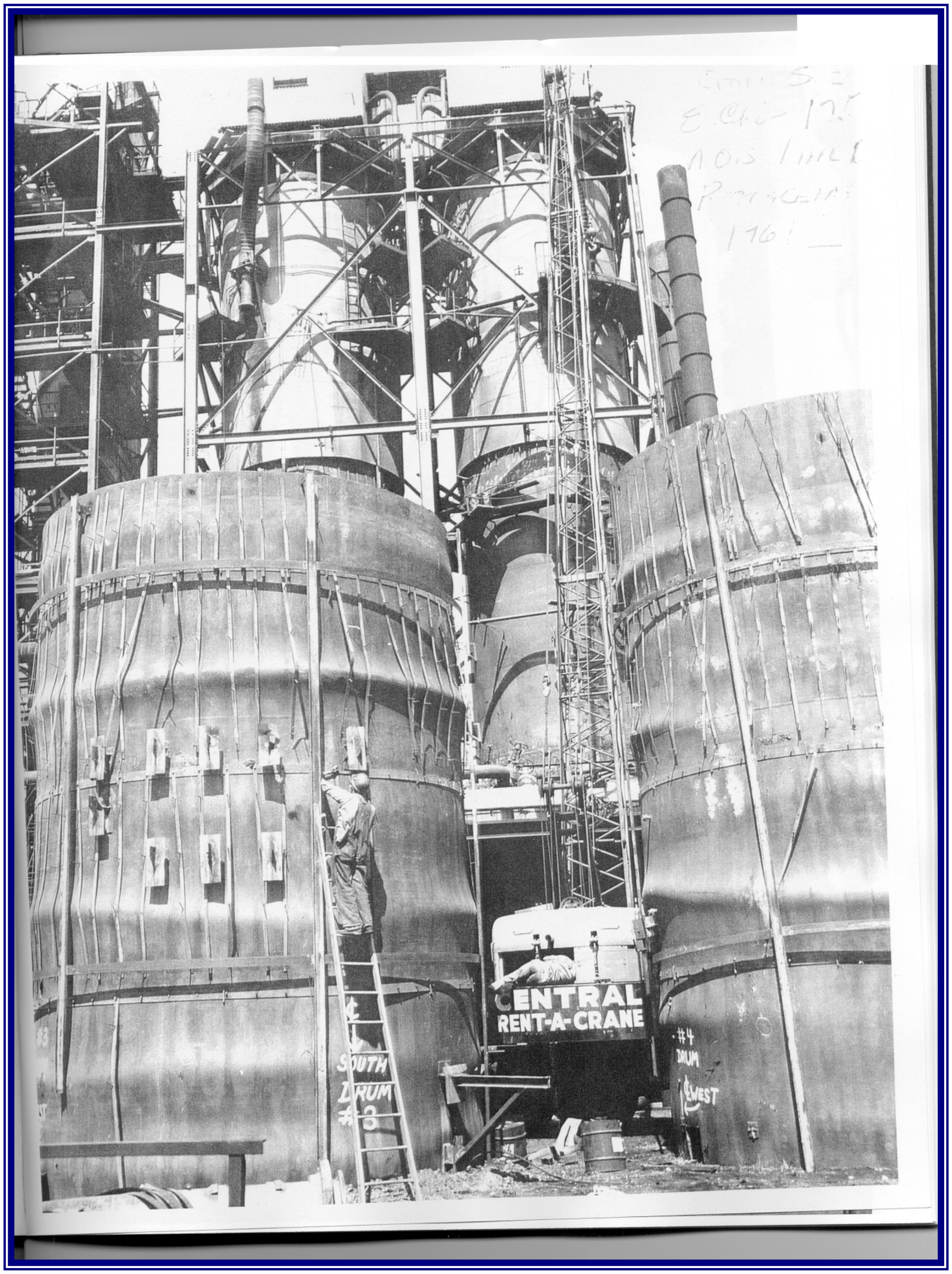

Figure 2 Coke Drum Shell Bulging

Petroleum coke produced by the delayed coking method has been commercially manufactured for more than 70 years. In the last decade, US petroleum coke production has been steadily increasing. Swain [6] (1997), predicts that production of petroleum coke in the U.S. will continue to increase as refiners continue to process more lower quality crudes than in the past. To meet increased demand for coke production, refiners either have to shorten the coking cycle or add coking units, or both.

DESCRIPTION OF "BULGING/CRACKING PHENOMENA"

Weil and Rapasky [1] (1958) identified radial bulging as a "reoccurring difficulty" that existed in essentially all operating coke drums of the time. Through extensive research carried out on a total of sixteen coke drums erected between 1938 and 1958, they identified a radial growth varying from almost negligible to as much as 0.3" per year. The rate of bulging was found to be directly attributable to the "quenching portion" of the operating cycle. They also recognized that the girth seams, due to the higher yield strength of the weld metal, tended to augment the bulging causing a "constrained balloon shape" as illustrated in Fig.3.

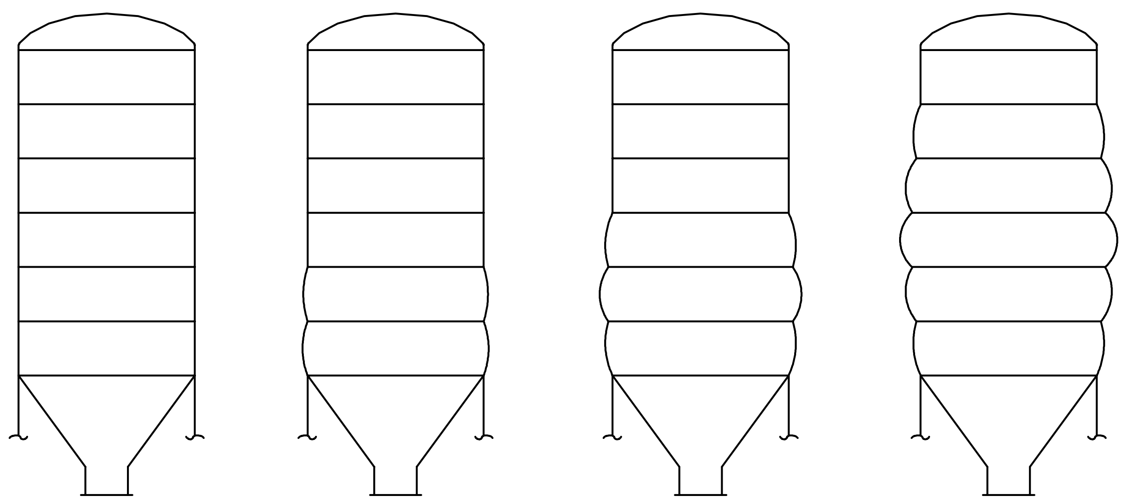

FIG 3 -- SUCCESSIVE STAGES IN BULGING DEFORMATION IN COKE DRUMS (TO AN EXAGGERAED SCALE) (REF. 1)

As a result of the restraint caused by the weld seams, the base material tends to become thin and ultimately fail via through wall cracking. The bulging is most severe in the lower cylindrical portion of the vessel, typically the first 40 to 50 feet above the cone section. This section of the vessel experiences the highest quench rates during the quench cycle. Typical rolled and welded construction of coke drums will place 4 to 5 circumferential seams in this 50 foot +/- section of the vessel, depending on the width of plate used for each shell course.

Through their studies, Weil and Rapasky [1] (1958) observed that high quenching rates produced thermal gradients in excess of 10°F per inch; lower quenching rates produced smaller gradients thus less bulging. To measure this effect they developed a "Unit Quench Factor" (UQF) Fig.4, that is the ratio of water-quenching time in minutes to the coke yield per drum in tons. Utilizing the resulting data they theorized that when the UQF is greater than 0.50 the bulging is minimal, when the UQF is greater than 0.80 the bulging is all but non-existent. The UQF is directly proportional to the rate of water injection during the quench cycle, the slower more controlled the quench the greater the UQF and consequently less bulging. In today's market few owners have the option of longer cycle times. To the contrary, the trend is for even shorter cycles. The result of which is a higher UQF that will ultimately reduce the overall life span of the vessel.

Unit No.	Water-Quenching Time (Minutes)	Coke Capacity (Tons)	Unit Quenching Factor Minutes	Relative Severity of Bulging Distortion
9	90	380	0.24	Severe
8	100	370	0.27	Severe
7	90	310	0.29	Severe
1	140	180	0.78	Negligible
5	135	170	0.80	Negligible
2	150	170	0.88	Absent
6	180	180	1.00	Absent

$$UQF = \frac{\text{water - quenching time (minutes)}}{\text{coke capacity (tons)}}$$

FIGURE 4 -- COMPARISON OF QUENCHING METHODS AND GROWTH ON VARIOUS COKING (REF 1)

In recent years there have been a number of studies undertaken and papers written that substantiate the conclusions of Weil and Rapasky [1] (1958).

- Penso, et. al.[5] (1999), suggest that low cycle thermal fatigue is the most common failure mechanism of a coke drum. The authors state in their conclusion that thermal shock is the main mechanism for the initiation of these cracks. They further concluded additional analysis of the cooling cycle is warranted in that the cooling cycle affects the severity of thermal shock. The authors also concluded that the severity of thermal shock is the main crack starter.
- Livingston and Saunders [4] (1998) report the coke drums in their survey began to through–wall crack at roughly 2,400 cycles. The frequency of through-wall cracking increased correspondingly with the number of cycles see Fig.5.

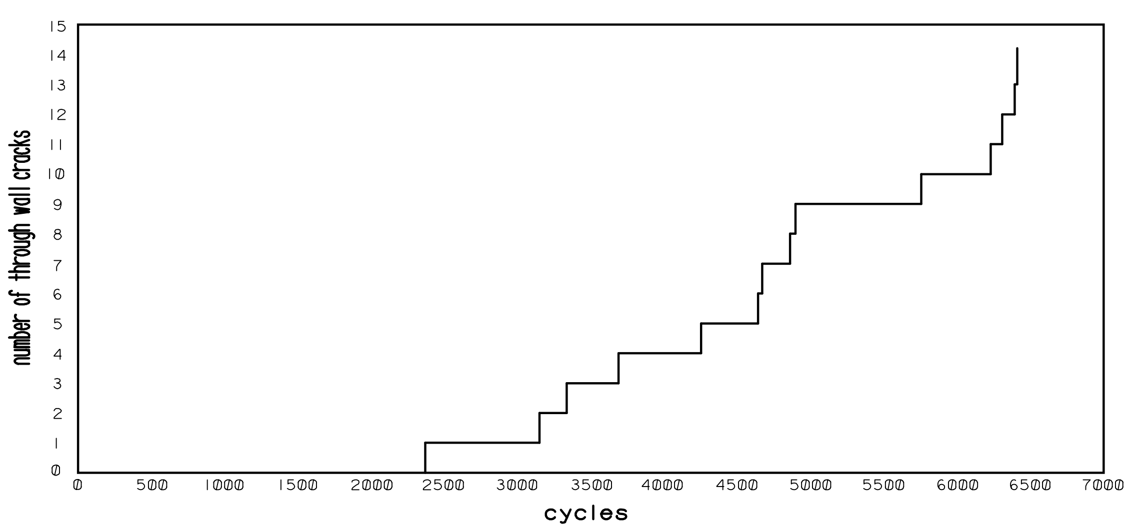

FIGURE 5 -- REPRESENTATIVE CUMULATIVE THROUGH WALL CRACK PROGRESSION (REF.4)

- Antalffy, et al. [3] (1999) cites at least three additional examples of recent papers which reference the bulging phenomena. He also cites that Boswell and Ferraro [2] (1997) and others as concluding the high relative strength of the circumferential weld metal as compared to the lower strength of the adjacent base metal to be the cause of the bulging

It is common industry knowledge through thermal and stress analyses of operating units, that the higher strength of the weld metal in the circumferential seams tends to have a stiffening effect which increases stress leading to distortion and cracking. The longitudinal weld seams required to make the shell courses are reported to be unaffected by the thermal cycling except where these seams intersect the circumferential seams. In the bulge areas near the circumfrential seams, the longitudinal weld seams are also affected by the thinning effect and will crack, given enough thermal cycles.

CONVENTIONAL DESIGN METHODOLOGY

The normal method of designing the shell courses of coke drums is to base the thickness of the material on the specified design pressure. Generally the pressure is specified as varying linearly from a minimum value at the top of the vessel to a maximum at the bottom flange. Because overall vessel cost is a function of weight and thickness, the tendency is to design each shell course for the design pressure specified at the bottom of the course. As a result, there are typically step reductions in thickness from one shell course to the next as shown in Figure 6. The resulting weld profile compounds the stiffening effect already present due to the higher yield strength of the weld metal, see Figure 7.

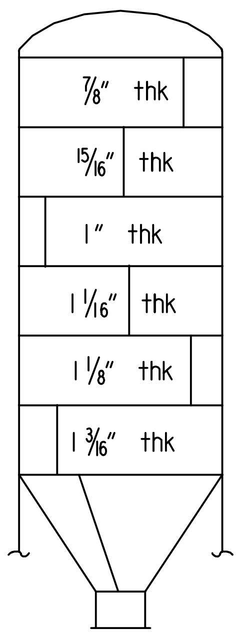

FIG 6 -- TYPICAL SHELL THICKNESS REDUCTION

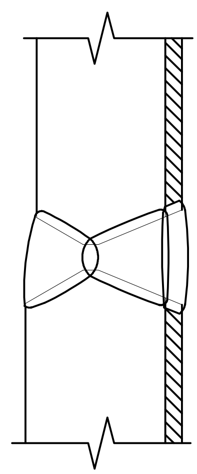

FIGURE 7 -- WELD PROFILE

SPECIFICATIONS INTENDED TO INCREASE VESSEL LIFE

As a result of the recent interest in improving coke drum reliability, there have been a number of measures developed or proposed that are intended to mitigate the stiffening effect of the weld seams. These measures have be incorporated into numerous procurement specifications that are intended to address the bulging/cracking phenomena and increase vessel life. For the most part these requirements are aimed at reducing the discontinuity effect at the circumferential weld seam. The most common of these specifications are as follows:

- Weld metal yield strength to be within a close percentage of base metal yield (e.g. - 0%, +10%) .
- "Blend grinding" the weld profile.
- Specifying higher alloy materials, i.e. 2 ¼ Cr – 1 Mo, and higher.
- Requiring more nondestructive examinations and using more restrictive nondestructive examination acceptance criteria than the construction code requires.
- Maintaining a uniform shell thickness through out the vessel.
- Specifying materials greater than two inches in thickness.

Though most have technical merit, the resulting improvement may only be incremental and not necessarily practical. For example, specifying a maximum allowance of strength mismatch between the weld metal and base metal is difficult at best due to the many variables involved. The actual yield strength of the base metals when compared to commercially available weld metals is typically more than 10% lower. (See figure 8) The yield strength of base metals and weld metals also vary with temperature, which may make the yield strength differential greater than 10% at elevated temperatures. Controlling weld metal yield strengths to a specific minimum/maximum in relation to the as-supplied base metal typically will disallow the use of the most productive weld processes, driving costs up.

Base Metal	Type	Tensile ksi	Yield Min. (typ) ksi	Weld Metal	Tensile ksi	Yield Min. (typ) ksi
A516-70	Carbon Steel	70-90	38 (46)	EM12K	70-95	58 (61)
A204 C	Carbon –½ Moly	75-95	43 (52)	EA2	70-95	58 (61)
A387-11, CL2	1 ¼ Cr – ½ Moly	75-100	45 (58)	EB2	80-100	68 (75)
A387-12, CL2	1 Cr – ½ Moly	65-85	40 (50)	EB2	80-100	68 (75)
A387-22, CL2	2 ¼ - 1 Moly	75-100	45 (58)	EB3	90-110	67 (80)
405 (clad)	13 Cr	60-90	25 (36)	ERNiCr-3	80-95	40 (52)
410S (clad)	12 Cr	60-90	30 (36)	ERNiCr-3	80-95	40 (52)
Note: All weld metal and base metal in typical PWHT condition for material combinations. All weld metal data is from SAW (submerged arc welding) process						

Figure 8, Typical Plate and Weld Metal Properties [8]

Blend grinding of weld profiles reduces the geometric stress raiser effects near the weld joint. Blend grinding is cost effective if properly specified and managed. There is a modest additional cost that is easily justified in extending the service life of the weld joint before it requires repair.

The use of uniform shell thickness throughout the critical area of the vessel has an added material and labor cost, but as stated earlier in this paper, not keeping a uniform thickness will increase the stiffening effect of the weld metal used for welding the circumfrential weld joints. The specifying of very thick and uniform shells will reduce the peak stresses caused by the thermal cycles somewhat, but will not reduce the effects of the circumferential seams acting as stiffeners during the quench cycle.

Higher alloys such as the 2 ¼ Chrome-1 Moly types are thought to be able to resist the thermal cycling better because of their higher yield and better creep and creep-fatigue resistance. This may increase the useful life and slow down bulging. However, most of the newer drums manufactured from this alloy have not seen sufficient coke production cycles to determine if this is a major improvement.

Some specifications are requiring increased nondestructive examinations (NDE) to be performed and the acceptable flaw size reduced in an attempt to get more uniform weld joint properties. This increases costs without having a significant effect on the basic problem of the circumferential weld joints acting as stiffeners.

There may be other proposed solutions to this problem of which the authors are unaware. These may have merit as well in reducing the potential for bulging and through-wall cracking. Only the most common solutions are presented here.

ELIMINATION OF CIRCUMFERENTIAL WELD SEAMS

It is common industry knowledge through thermal and stress analyses of operating units that the higher strength of the weld metal in the circumferential seams tends to have a stiffening effect which increases stresses leading to the distortion and cracking. It is also common knowledge that the longitudinal seams are unaffected, except where they intersect the circumfrential seams.

It appears that the best solution to the problem of girth seam distortion and cracking is the elimination of the circumferential weld seams in the area of concern. This eliminates the need for some of the additional requirements currently being specified.

Incorporating technology and know how from other applications, shell plates have been successfully fabricated with the long side orientated vertically. This allows fabrication of cylindrical shell sections of up to approximately 46 feet in height without a circumferential weld seam. Plate size is only limited by the steel mill manufacturing capability. Currently the largest plates available are in the range of 46 feet in length depending on specified thickness and alloy. The resulting cylindrical shell section can then be located in the area of the vessel that will experience the most severe thermal cycles (Fig. 9). Depending on plate size limitations, up to five (5) circumferential weld seams can be eliminated.

In late 1997 Chicago Bridge & Iron Company performed an extensive research [(7)] and analysis project to investigate the feasibility of design, fabrication and erection of a "vertical seam" coke drum. The resulting conclusion was that such a vessel could be economically produced as reported by Antalffy, et. al. (1999). This method will provide a uniform thickness throughout the cylindrical portion of the vessel. The vertical seam concept can easily be applied to new construction (shop built up or field erected). It can also be applied to retrofit applications where the lower cone and top head sections of the vessels are reused.

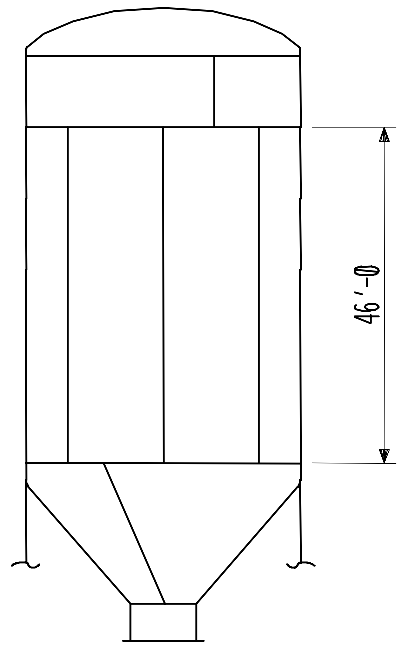

FIG. 9 — ELIMINATION OF CIRCUMFERENTIAL WELD SEAMS

CONCLUSIONS

The bulging and eventual cracking of the circumferential weld seams located in the critical quench area of a coke drum is a problem that has plagued the coking industry almost from its inception. There is general agreement that the root cause is low cycle thermal fatigue from the quenching operation. The quench rate being the significant parameter. All have recognized the stiffening effect of the circumferential weld seams primarily caused by the weld metal to base metal yield strength mismatch. Accordingly, the quench rate and the use of circumfrential weld joints are major factors in determining the useful life of coke drums.

Due to the increased use of heavier feedstocks and a higher demand for industrial coke, the problem has recently received a renewed interest. To keep up with increased demand, many coke drums are operating using quench rates that accelerate the distortion leading to an earlier occurrence of cracking.

Industry has recently developed coke drum procurement specifications which include requirements that provide incremental enhancements to vessel reliability including requirements meant to address bulging and the through wall cracking associated with the bulging.

Chicago Bridge & Iron Company's vertical seam concept is the first significant design change in coke drum fabrication specifically designed to eliminate a major factor contributing to this problem since the delayed-coking process was developed. This concept is both technically and commercially feasible to manufacture using materials and welding processes/electrodes commonly specified for coke drum service.

A vessel fabricated or retrofitted utilizing the vertical seam technology will provide the owner with a vessel that has a longer more reliable life than those designed and manufactured using conventional designs that place circumfrential weld seams in the critical area of the vessel.

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